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Wheat basal crop coefficients determined by normalized difference vegetation index

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Abstract Crop coefficient methodologies are widely used to estimate actual crop evapotranspiration (ET_c) for determining irrigation scheduling. Generalized crop coefficient curves presented in the literature are limited to providing estimates of ET_c for "optimum" crop condition within a field, which often need to be modified for local conditions and cultural practices, as well as adjusted for the variations from normal crop and weather conditions that might occur during a given growing season. Consequently, the uncertainties associated with generalized crop coefficients can result in ET_c estimates that are significantly different from actual ET_c, which could ultimately contribute to poor irrigation water management. Some important crop properties such as percent cover and leaf area index have been modeled with various vegetation indices (VIs), providing a means to quantify real-time crop variations from remotely-sensed VI observations. Limited research has also shown that VIs can be used to estimate the basal crop coefficient (K_{cb}) for several crops, including corn and cotton. The objective of this research was to develop a model for estimating K_{cb} values from observations of the normalized difference vegetation index (NDVI) for spring wheat. The K_{cb} data were derived from back-calculations of the FAO-56 dual crop coefficient procedures using field data obtained during two wheat experiments conducted during 1993–1994 and 1995–1996 in Maricopa, Arizona. The performance of the K_{cb} model for estimating ET_c was evaluated using data from a third wheat experiment in 1996–1997, also in Maricopa, Arizona. The K_{cb} was modeled as a function of a normalized quantity for NDVI, using a third-order polynomial regression relationship ($r^2 = 0.90$, $n = 232$). The estimated seasonal ET_c for the 1996–1997 season agreed to within −33 mm (−5%) to 18 mm (3%) of measured ET_c. However, the mean absolute percent difference between the estimated and measured daily ET_c varied from 9% to 10%, which was similar to the 10% variation for K_{cb} that was unexplained by NDVI. The preliminary evaluation suggests that remotely-sensed NDVI observations could provide real-time K_{cb} estimates for determining the actual wheat ET_c during the growing season.

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Introduction

An important requirement for attaining proper irrigation scheduling is the determination of actual crop evapotranspiration (ET_c) during the growing season. The crop coefficient (K_c) methodology (Doorenbos and Pruitt 1977) was developed to provide growers with a simple ET_c prediction tool for guiding irrigation management decisions. This widely applied approach to ET_c estimation is governed by empirically developed K_c ratios of measured ET_c and a reference evapotranspiration, traditionally based on either grass or alfalfa evapotranspiration. For grass-reference evapotranspiration (ET_o), K_c is defined as:

$$K_c = ET_c/ET_o \tag{1}$$

During the growth season, values of K_c for most agricultural crops increase from a minimum value at planting in relation to changes in canopy development until a maximum K_c is reached at about full canopy cover. At some point in the season after full cover is reached, the K_c will tend to decline, the extent of which is primarily dependent on the particular growth characteristics of the crop (Jensen et al. 1990) and the irrigation management during the late season (Allen et al. 1998). A crop coefficient curve is the seasonal distribution of K_c, often expressed as a smooth continuous function in time or some other time-related index.

The Food and Agricultural Organization (FAO) of the UN, Paper 56 [FAO-56] (Allen et al. 1998) presented revised crop coefficient procedures for estimating ET_c, which are expected to become the de facto crop coefficient standard for the USA and abroad. In addition to the single K_c approach, FAO-56 introduced dual crop coefficient procedures where the single K_c is separated into a basal crop coefficient, or K_{cb} (primary crop transpiration), and a soil evaporation coefficient (K_e), where

$$K_c = (K_{cb} + K_e) \tag{2}$$

The dual crop coefficient method with K_{cb} and K_e allows computation of more precise estimates of daily ET_c, particularly for days following irrigation or rain, when increased soil evaporation can cause actual K_c values to deviate significantly from a single, time-averaged K_c curve. The FAO-56 publication provides typical development lengths for growth stages and tabularized K_{cb} values for most agricultural crops. However, since the development lengths and K_{cb} values provided in FAO-56 are intended to strictly represent conditions for standard crop densities and optimum agronomic and water management practices, the publication strongly encourages local calibration of development lengths and, if warranted from research findings, recommends modifying K_{cb} curves to more adequately reflect the crop water use behavior under the local conditions (Allen et al. 1998). Thus, using time-based K_{cb} curves can become problematic in that one needs to estimate crop development rate and maximum K_{cb} early in the season to accommodate atypical crop development and water use patterns that may arise later in the season due to weather anomalies, non-standard plant stands, or sub-optimum nutrient or water inputs.

Multispectral vegetation indices (VIs), computed from crop canopy reflectance measurements, were demonstrated to function effectively as near real-time surrogates of K_{cb} for corn (Bausch and Neale 1987, 1989; Bausch 1995), beans (Jayanthi et al. 2001), and cotton (Neale et al. 1996). A few of the benefits for the VI-based crop coefficients reported in these studies include the ability to account for variations in plant growth due to abnormal weather conditions, and improved irrigation scheduling due to better estimation of water use and more appropriate timing of irrigations. Multispectral VIs, computed as differences, ratios, or linear combinations of reflected light in the visible (blue, green, and red) and near infrared (NIR) have been found to be closely related to crop growth parameters, such as leaf area index (Moran et al. 1995) and vegetation cover (Heilman et al. 1982; Jackson and Huete 1992). The normalized difference vegetation index, or NDVI [NDVI = (NIR – red)/(NIR + red)] and the soil adjusted vegetation index (SAVI; Huete 1988) are the two predominant VIs that are used for estimating crop coefficients.

In the arid, desert regions of the southwestern US, high water use requirements coupled with increasing costs for water in the region require wheat growers to implement irrigation practices that will lead to increased water use efficiency. One of the most important elements in the area will be a greater emphasis on appropriate irrigation management. The focus of this paper is to provide a means for improving wheat irrigation scheduling and management in the area using real-time crop coefficient estimation. The objectives were to develop a model for determining wheat K_{cb} directly from NDVI observations; and to provide an evaluation of wheat evapotranspiration calculated using NDVI-based K_{cb} estimates within FAO-56 procedures.

Methods and materials

A series of four, free-air CO_2 enrichment (FACE) experiments were conducted with a hard red spring wheat (*Triticum aestivium* L., cv. Yecora Rojo) between

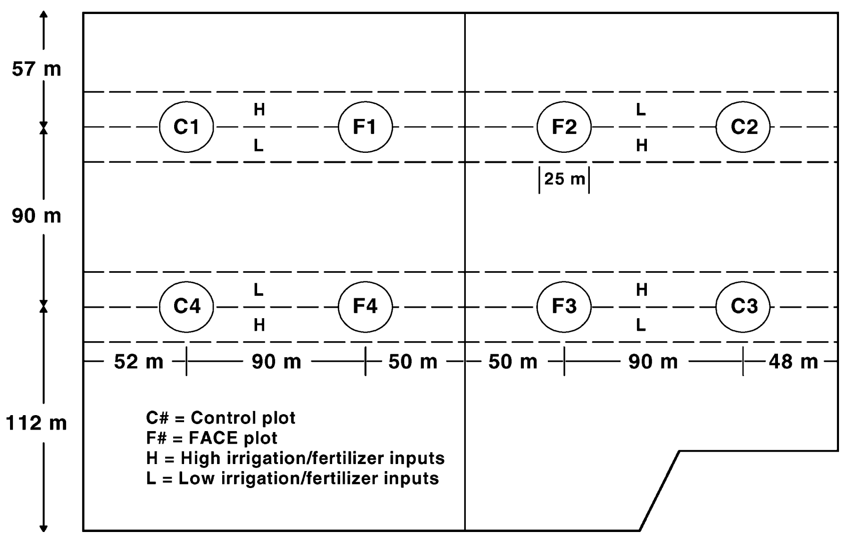

Fig. 1 Field plot plan for the 1993–1994 to 1996–1997 FACE experiments showing four replicate circular FACE plots and four corresponding control plots. All circular main plots were split into semicircular sub-plots of either high and low irrigation inputs (1993–1994) or high and low nitrogen fertilizer inputs (1995–1996 and 1996–1997)

1991 and 1997 in central Arizona, at the University of Arizona, Maricopa Agricultural Center (MAC), Maricopa, Arizona (Kimball et al. 1999). Data acquired during three of the seasons (1993–1994, 1995–1996, and 1996–1997) were used to develop and test an NDVI-based K_{cb} model for wheat (data for the first FACE wheat experiment, 1992–1993, were not included due to limited NDVI measurements). During the FACE wheat studies, data were collected for a wide range of plant, soil, and meteorological parameters. Additional information about the experimental procedures, descriptions on the methodology of data collection, and crop evapotranspiration can be found in Wall and Kimball (1993), Kimball et al. (1995, 1999), Hunsaker et al. (1996, 2000), and Pinter et al. (1996, 2000).

The FACE experiments investigated the interactive effects of elevated CO_2 and irrigation water supply (1993–1994) and elevated CO_2 and nitrogen level (1995–1996 and 1996–1997) on wheat. The experimental design for theses experiments included eight, circular main plots, 25 m in diameter, placed within a 9-ha wheat field (Fig. 1). In four FACE treatment plot replicates, the air above the wheat canopy was enriched with CO_2 at a concentration of $\asymp$550 μmol mol^{-1}. In the other four plots that comprised the control treatment, wheat was grown under ambient air conditions, where daytime ambient CO_2 concentrations within the plots averaged $\asymp$360 μmol mol^{-1} during the three wheat seasons. Although the control and FACE replicates were separated center to center by 90 m (Fig. 1), Kimball et al. (1999) estimated that the CO_2 concentration within control plots averaged 15 μmol mol^{-1} or about 4% higher than that of the actual ambient air at MAC, indicating that control plots were slightly contaminated by FACE plots. Additional sub-treatments with high and low water supply (1993–1994) and high and low nitrogen level (1995–1996 and 1996–1997) were embedded within the eight main treatment plots. However, for this paper, only data for the four replicated sub-treatment control plots within each experiment (denoted as C–H plots) that were grown under ambient CO_2 and with high inputs for irrigation and nitrogen were considered. Note that ambient CO_2 concentrations are expected to continue increasing and it is likely that within the near future the atmospheric CO_2 will be 15 μmol mol^{-1} or more higher than it was at the time of the FACE experiments in the mid-1990s. Although a significant change in the wheat ET_c of C–H plots due to the 4% increase in CO_2 would be highly unlikely, the slightly higher than ambient CO_2 concentrations in the C–H plots would tend to increase the applicability of this wheat data set for use in a future higher-CO_2 world.

Crop culture

The spring wheat was planted on flat ground in mid-December in east-west rows, spaced 0.25-m apart. Crop emergence was observed on 28 December 1993, 1 January 1996, and 3 January 1997, and the plant density at complete emergence varied from 186 to194 plants m^{-2} for the three seasons (Kimball et al. 1999). A combination of chemical and biological methods were used to control insects and weeds. The C–H plots received a total of 261 kg N ha^{-1} during 1993–1994, and 350 kg N ha^{-1} during both 1995–1996 and 1996–1997. Final harvests of grain occurred on 1 June 1994, 29 May 1996, and 28 May 1997, and mean grain yields for the C–H treatment were 7,436 $\pm$ 872, 7,400 $\pm$ 662, and 5,977 $\pm$ 81 kg ha^{-1}, respectively.

Soil characteristics

The soil at the FACE experimental site is classified as a Trix clay loam [fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents] (Kimball et al. 1999). Volumetric soil water contents at 100% and 0% total available water (TAW) averaged 30 and 20% for the top 0.7 m of the soil profile, respectively, whereas they averaged only 22 and 12%, for the subsurface profile (0.7–2.0 m), respectively (Hunsaker et al. 1994).

Irrigation management

Five and nine days after planting the 1993–1994 experiment, 13 and 17 mm of water was applied, respectively, to all plots with a portable sprinkler systems for seed germination (Hunsaker et al. 1996). Six and 13 days after planting the 1995–1996 and 1996–1997 experiments, respectively, 30 mm of water was applied to all plots for germination (Hunsaker et al. 2000). Afterwards, for all experiments, irrigation water was supplied with a subsurface drip irrigation system that included micro-tube lines spaced every 0.50-m apart, buried 0.18–0.25 m below the soil surface, parallel to the wheat rows. For all wheat seasons, the C–H plots were irrigated at approximately 30% depletion of the available soil water with an amount calculated to replace 100% of the estimated wheat ET_c since the last irrigation (adjusted for rainfall), as determined by the irrigation scheduling program, AZSCHED (Fox et al. 1992). The AZSCHED program uses a single K_c approach and an ET_o calculation based on equations presented in FAO-24 (Doorenbos and Pruitt 1977) and therefore differs considerably from the methods used in the FAO-56 dual crop coefficient procedures. The relatively small allowable depletion percentage of 30% used within AZSCHED resulted in frequent, light irrigations to C–H plots. This approach was intended to minimize water stress conditions on the wheat that may occur by any under prediction of ET_c based on the single K_c used in AZSCHED. Cumulative amounts of the metered irrigation applications from planting through harvest for the C–H plots averaged 650, 653, and 621 mm for the 1993–1994, 1995–1996, and 1996–1997 seasons, respectively, and the cumulative rainfall (planting through harvest) measured at the field site was 61, 39, and 35 mm, respectively (Hunsaker et al. 1996, 2000).

Soil water content measurements

Volumetric soil water contents were measured in each plot using time-domain-reflectometry (TDR) and neutron scattering equipment installed at the beginning of each experiment (Hunsaker et al. 1996; Hunsaker et al. 2000). The TDR system (Trase1, Soil-Moisture Equip. Corp., Santa Barbara, CA) was used to measure the integrated volumetric soil water content from 0 to 0.30 m below the soil surface. (Note: product names and company names are included for the benefit of the reader and do not imply endorsement of the product by the authors or the US Department of Agriculture). Neutron probe access tubes were installed to a depth of 2.0 m at a location near the TDR in each plot. Site-calibrated neutron probes (Model 503, Campbell Pacific Nuclear, Martinez, CA) were used to measure the volumetric water contents in 0.2-m increments from 0.40 to 2.0 m. For all experiments, the TDR and neutron probe measurements were made on the same days for all plots during early morning hours. The frequency of soil water content measurements varied from 3 to 11 days from crop emergence through early February for each year. After early February, the frequency of water content measurements varied from 2 to 8 days for each year until shortly before final harvest.

Crop canopy height, reflectance, and transmittance measurements

Wheat canopy height was determined from plants sampled from each plot at 7- to 10-day intervals throughout each season. Starting at crop emergence, canopy reflectance factors were measured in all plots two to five times per week during each of the three growing seasons (Pinter et al. 2000). Data were acquired in red (0.61–0.68 μm) and near-infrared (NIR, (0.79–0.89 μm) wavelengths using a 4-band Exotech hand-held radiometer (Model BX-100; Exotech, Inc., Gaithersburg, MD) equipped with 15° field-of-view optics. Data were collected at a morning-time period corresponding to a nominal solar zenith angle of 57°. The normalized difference vegetation index was computed as: NDVI = (NIR−red)/(NIR + red).

Every two to three weeks during the 1993–1994 and 1995–1996 seasons, and on days when canopy reflectance measurements were made, the fraction of the photosynthetically active radiation (PAR; 0.40–0.70 μm absorbed by the canopy (fA_{PAR}) was calculated from measurements of the incident, transmitted, and reflected components of the radiation balance using a 0.80-m long light bar (Model LI-191, Li-Cor, Inc., Lincoln, NE). The light bar measurements were made at a 45° diagonal with plant rows, both above and below the plant canopy in all treatment plots. Similar measurements were made at a separate bare soil plot in the same field. To compute fA_{PAR}, the fraction of PAR transmitted through the canopy (fT_{PAR}), the fraction of PAR reflected from the canopy, and the fraction of the PAR reflected from the soil, obtained from the light bar measurements, were used in the light balance equation described by Pinter et al. (1994).

Meteorological data and reference evapotranspiration (ET_o)

In FAO-56, Allen et al. (1998, pp65–86) describe methods for calculating grass-reference ET_o. The meteorological data used in the ET_o calculations for the study were provided by an AZMET weather station (Brown 1989) located on a well-watered grass site at MAC, ≍1.5 km from the FACE field. Both the station and field plots were surrounded by similarly cropped areas and the flat terrain at MAC did not present any obstacles that would deem the off-site weather station as being non-representative of evapotranspiration conditions at the field site. Daily AZMET data for solar radiation, air temperature, wind speed, and humidity were used to calculate daily ET_o for a short, 0.12-m height crop (similar to clipped grass) with the FAO Penman–Monteith equation (Allen et al. 1998, Eq. 6):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma 900/(T + 273)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

where ET_o = reference evapotranspiration (mm d^{-1}), R_n = net radiation (MJ m^{-2} d^{-1}), G = soil heat flux density (MJ m^{-2} d^{-1}), T = air temperature at 2-m height (°C) Δ= slope saturation vapor pressure curve (kPa C^{-} 1), γ= psychrometric constant (kPa °C^{-1}), e_s = saturation vapor pressure (kPa), e_a = actual vapor pressure (kPa), and u_2 = wind speed at 2-m height (m s^{-1}).

Evapotranspiration from soil water balance

The measured wheat ET_c that occurred between two successive soil water content measurement dates was calculated as the residual of the soil water balance equation (Jensen et al. 1990) and can be written as:

$$ET_c = \left(D_{r,2} - D_{r,1}\right) + I + R - DP \tag{4}$$

where ET_c is the total evapotranspiration (mm) between two successive soil water measurement dates, $D_{r,1}$ and $D_{r,2}$ are the measured root zone soil water depletion (mm) on first and second dates, respectively, and I, R, and DP are the depth of irrigation applied (mm), and the rainfall (mm) and the deep percolation (mm) that occurred between the two soil water measurements, respectively. For Eq. 4, the maximum depth of the effective wheat rooting depth (Z_r) was assumed to be 1.3 m. The assumption was based on detailed soil water extraction work by Erie et al. (1982) in Arizona, showing that 99% of irrigated wheat water uptake occurs in the upper 1.2–1.4-m soil depth. The 1.3-m maximum rooting depth was also supported by soil water depletion patterns observed for C–H plots during the three seasons (data not shown). When irrigation or heavy rainfall was added between two successive soil water measurements, an estimate of deep percolation was made. The estimate for DP was calculated as the amount of increased soil water storage (if any) that occurred within soil layers measured below 1.3 m following the wetting event. This technique does not provide an effective way to evaluate any deep percolation water below a depth of 2.0 m, nor a means to estimate any DP water possibly returning to the root zone under capillary action. Consequently, when imprecise estimates of actual DP are used in the water balance, errors can be introduced in the estimate for ET_c. However, evaluating changes in soil moisture below the rooting depth offered the best way to detect and approximate actual DP with any of the measurements made during these studies. Potential errors for measured ET_c due to uncertainties for DP will be discussed later in results and discussion.

Basal crop coefficient derivations

Soil water balance determinations of the measured wheat ET_c for two- to eleven-day intervals during the three seasons were used to derive K_{cb} estimates for each of the four C–H plot replicates. Derivation was accomplished by back-calculating a K_{cb} value for each interval based on the ‘‘known’’ value for the total ET_c during the interval from the soil water balance, a methodology similar to that used by Hunsaker et al. (2003). The FAO-56 dual crop coefficient procedures (Allen et al. 1998, pp135–158) were employed in the back-calculations to separate the measured ET_c into the basal and evaporation contributions, while considering the effects of water stress on the basal ET_c. The FAO-56 dual crop coefficient procedures describe the relationship between ET_c and ET_o upon separating the single K_c into the basal crop and soil water evaporation coefficients:

$$K_c = (K_{cb} + K_e) = ET_c/ET_o \tag{5}$$

where ET_c and ET_o are in mm d^{-1}.

The basal crop coefficient, K_{cb}, represents the ratio of ET_c/ET_o for conditions when, first, the soil surface layer is dry (i.e., when $K_e = 0$) and, second, the soil water within the root zone is adequate to sustain full plant transpiration (non-stressed conditions). When the soil surface is wetted following irrigation or rain, the FAO-56 dual crop coefficient procedures calculate the separate contribution to ET_c, apart from basal crop water use, due to soil evaporation described by the soil evaporation coefficient, K_e (Allen et al. 1998, pp142–158). The FAO-56 method uses a two-stage drying approach for determination of K_e. For stage 1 (energy limiting stage), evaporation from a wet soil surface proceeds at a maximum rate limited only by the energy available at the soil surface. Stage 1 ends when the cumulative evaporation from the soil surface exceeds readily evaporable water (REW), the maximum depth of cumulative evaporation without restriction during stage 1. For stage 2 (falling rate stage), evaporation from the soil surface decreases in proportion to the amount of water remaining in the surface layer until the cumulative evaporation reaches total evaporable water (TEW), the maximum depth of evaporation that can occur from the initially wetted surface layer during a complete drying cycle. REW is dependent upon the soil texture of the surface layer and normally varies between 8 mm and 12 mm for clay loam (Allen et al. 1998, Table 19). For the present analysis, a mid REW value of 10 mm for clay loam was assumed for all C–H replicates. TEW is dependent on the field capacity (θ_{FC}) and wilting point (θ_{WP}) volumetric soil water contents of the surface soil layer (Z_e) subject to drying by evaporation, and varies from 22 mm to 29 mm for the soil type as given in Table 19 of FAO-56. TEW for all C–H replicates was based on the mean soil water content values of 30 and 20% at field capacity and wilting point determined for the upper soil profile at the site, respectively, combined with the mid-range depth for Z_e (0.125 mm) in FAO-56, which resulted in a TEW of 25 mm, when calculated using equation 73 in FAO-56. Two other primary parameters required for determining K_e are (1) the daily fraction of the soil surface shaded by the canopy (f_c), or conversely the unshaded fraction ($1 - f_c$), and (b) the fraction of the soil surface wetted (f_w) during each irrigation and precipitation event (Allen et al. 1998, pp147–149). Values for the unshaded fraction of the canopy, $1 - f_c$, were approximated from the fraction of the incident PAR transmitted through the canopy (fT_{PAR}) determined with the light bar measurements made separately for each C–H replicate during the 1993–1994 and 1995–1996 wheat seasons. Daily values for fT_{PAR} ($\asymp 1 - f_c$) were then estimated by linear interpolation between days of light bar measurements. Because similar light bar measurements were not made in the 1996–1997 experiment, estimates of daily fT_{PAR} for replicates in that season were obtained from daily NDVI observations for the replicates using a calibration model developed from the 1995–1996 fT_{PAR} and NDVI data (Hunsaker et al. 2000). For all years and replicates, a value of 1.0 was assigned for f_w when rain or sprinkler irrigation occurred (i.e., the entire soil surface was assumed to have been wetted). Following subsurface drip irrigation events, the value used for f_w was calculated using the FAO-56 recommendations for subsurface drip systems (Allen et al. 1998, pp147), where $f_w = 0.30\ (1 - 0.67\ f_c)$. Following wetting events, a daily water balance of the exposed and wetted fraction of the surface soil layer was applied to calculate cumulative evaporation from the wet condition (Allen et al. 1998, Eq. 77).

When the available soil water of the effective crop rooting depth drops below a critical level, crop water stress can occur and reduce ET_c. The effects of water stress on ET_c (Allen et al. 1998, pp161–170) are estimated by multiplying K_{cb} by the water stress coefficient (K_s) so that:

$$ET_c = (K_{cb}K_s + K_e)ET_o \tag{6}$$

where $K_s < 1$ when the available soil water is insufficient for full ET_c, and $K_s = 1$ when there is no soil water limitation on ET_c. Determination of K_s requires computation of the daily soil water balance of the effective root zone (separate from the surface soil evaporation layer daily water balance) to estimate the root zone soil water depletion (D_r) for each day of the season. The value of K_s is dependent upon D_r, TAW for the effective crop rooting depth (Z_r), and a soil depletion fraction, p, which is limited between 0.1 and 0.8. The p value represents the fraction of TAW that can be depleted from the rooting depth before water-stress occurs. For a given day i, the calculation of K_s is given as:

$$K_{s,i} = (TAW_i - D_{r,i})/(TAW_i - pTAW_i) \tag{7}$$

where $K_{s,i} = 1$ when $D_{r,i}$ is smaller than equal to $pTAW_i$ and $K_{s,i}$ is <1 otherwise. TAW_i is calculated as:

$$TAW_i = 1000(\theta_{FC} - \theta_{WP})Z_{r,i} \tag{8}$$

where TAW_i is in units of mm, θ_{FC} and θ_{WP} are in $m^3\ m^{-3}$, and $Z_{r,i}$ is in m.

For the present analysis, the site determined mean values for θ_{FC} and θ_{WP} of 0.30 and 0.20 $m^3\ m^{-3}$, respectively, were used for soil layers from 0 to 0.7 m, whereas the site determined values of 0.22 and 0.12 $m^3\ m^{-3}$, respectively, were used for θ_{FC} and θ_{WP} for soil layers below 0.7 m, for all replicates and years. Thus, when the maximum Z_r of 1.3 m is attained, TAW is equal to130 mm with Eq. 8. A typical implementation of the FAO-56 procedures is to assume that the daily increase for Z_r up to the maximum occurs proportionately to the increase in daily K_{cb} to its maximum. However, this approach was not used for

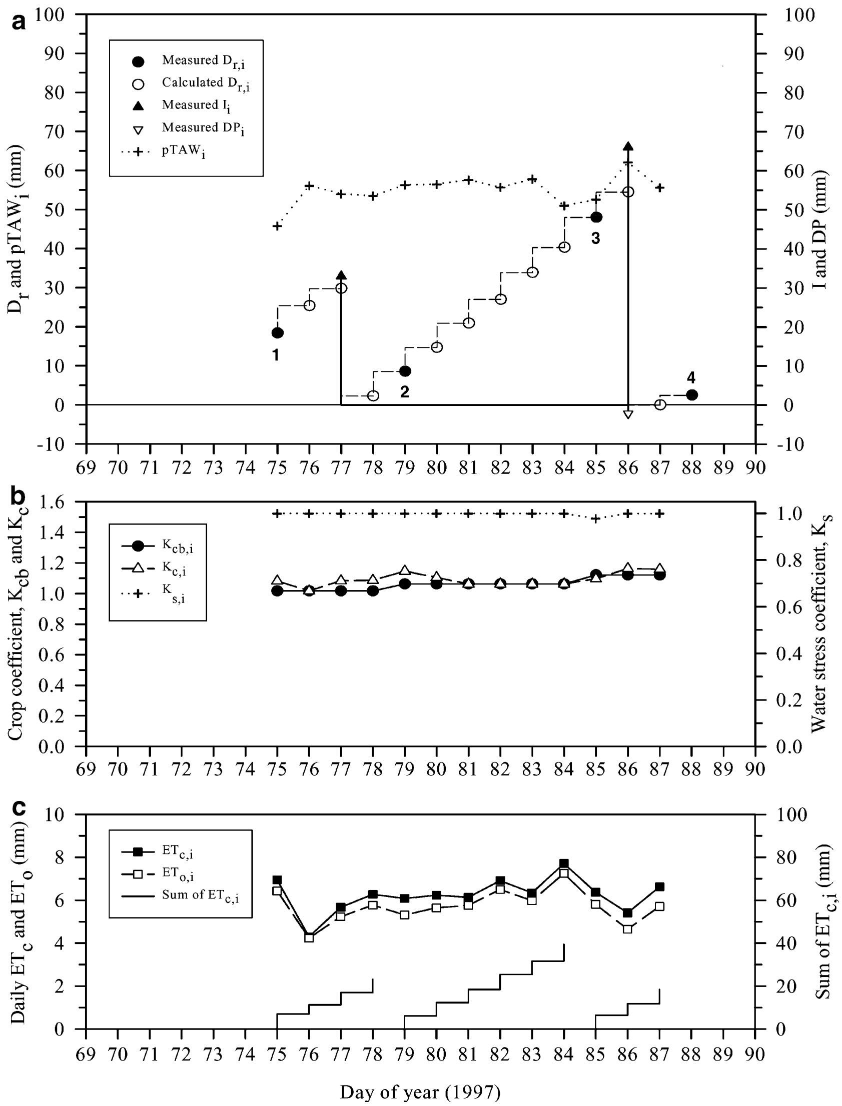

Fig. 2 Back-calculation process illustrated for a C–H replicate during the 1996–1997 wheat season: **a** daily root zone water balance components for three measurement intervals from DOY 75 to DOY 87 showing measured and calculated daily root zone depletion ($D_{r,i}$), measured irrigation (I_i) and deep percolation (DP_i), and the estimated daily upper limit for allowable soil water depletion ($pTAW_i$); **b** derived daily basal crop coefficients ($K_{cb,i}$), and estimated daily total crop coefficients ($K_{c,i}$) and water stress coefficients ($K_{s,i}$); **c** daily estimated crop evapotranspiration ($ET_{c,i}$), daily calculated reference evapotranspiration ($ET_{o,i}$), and daily summation of $ET_{c,i}$ for each measurement interval

the K_{cb} back-calculation derivations since it requires the K_{cb} curve to be already established ahead of time. Consequently, for estimating daily TAW by Eq. 8, it was assumed that the daily Z_r for all replicates and years increased linearly from a minimum value of 0.25 m at crop emergence (Allen et al. 1998, pp279) to the maximum of 1.3 m in proportion to the increase in measured canopy height. The canopy height approximation for Z_r was found to agree reasonably well with monthly root biomass depth measured for replicates by Wechsung et al. during the three seasons (Wechsung et al. 1995, 1998). The tabulated depletion fraction (p) of 0.55 for wheat (FAO-56, Table 22) was adjusted daily for atmospheric demand following the FAO-56 numerical approximation procedures, where daily p = 0.55 + 0.04 (5 − ET_c).

Starting with the first soil water measurement after crop emergence, the wheat season was partitioned into a series of time intervals whose lengths (2–11 days) were established by the number of days between two successive soil water content measurements. The total measured ET_c for each interval was known from the soil water balance and the daily ET_o for each day in the interval was calculated by Eq. 3 using daily weather data. Thus, for a given interval, the daily values for K_{cb}, K_e, and K_s were back-calculated as a consequence of the values for total measured ET_c, calculated daily ET_o, and the soil and crop parameter estimates used in FAO-56. This can be described for a given interval from day 1 to day n-1 as:

$$\sum_{i=1}^{n-1} \mathrm{ET}_{c,i} = \sum_{i=1}^{n-1} \left(K_{cb,i}K_{s,i} + K_{e,i}\right)\mathrm{ET}_{o,i} \tag{9}$$

where day 1 is the day a soil water content measurement was made in the morning, and day n is the next day a soil water content measurement was made in the morning; the summation of $ET_{c,i}$ from day 1 to day $n-1$ equals the measured total ET_c for the interval; $K_{cb,i}$, $K_{s,i}$, and $K_{e,i}$ are the basal crop, water stress, and soil evaporation coefficients on day i, respectively, and $ET_{o,i}$ is the grass-reference evapotranspiration on day i. For each C–H plot, daily time-step calculations for K_{cb}, K_e, K_s, ET_c, ET_o, and the other required parameters of the FAO-56 dual crop coefficient procedures were made within a spreadsheet that contained all the computations for each day of the growing season. Derivation involved adjusting the $K_{cb,i}$ value for the given measurement interval until the right-hand side of Eq. 9 matched the quantity on the left-hand side of the equation, i.e., until it agreed with the total ET_c that was measured for the interval. The $K_{cb,i}$ were assumed to be constant for all days within the interval, i.e., each day within the interval had the same K_{cb} value.

The back-calculation process is illustrated for three sequential soil water measurement intervals beginning on day of year (DOY) 75 and ending on DOY 87 for one of the C–H replicates in 1997 (Fig. 2). The measured ET_c for the four-day interval from DOY 75 to 78 was 23 mm. Daily root zone water balance computations for the interval were initiated at the beginning of DOY 75, starting with the soil water depletion (D_r) that was measured in the morning of that day (shown in Fig. 2a as the enclosed circle designated as 1). The open circles shown on days following the measured D_r at 1 represent the D_r at the beginning (morning) of each new day in the interval, as determined by the root zone water balance after input of the D_r, irrigation, rain, ET_c, and DP were made through the end of the previous day. Derivation of the constant K_{cb} value for the four-day interval ended when a given K_{cb} (Fig. 2b) resulted in the summation of the daily ET_c for the interval being equal to the measured ET_c, or 23 mm (Fig. 2c). The daily values of pTAW (Fig. 2a) represent the upper limit for soil water depletion, above which crop water stress occurs causing K_s (Fig. 2b) to decrease below a value of 1.0. The effect of water stress on the derivation is illustrated for the three-day interval starting on DOY 85 and ending on DOY 87, where D_r at the end of DOY 85 (above the enclosed circle designated as 3 in Fig. 2a) was greater than pTAW for that day. The constant K_{cb} derived for the interval was 1.12, but because K_s was less than 1.0 on DOY 85, the K_c on DOY 85 was slightly less (1.10) than the K_{cb} (Fig. 2b). When water stress did not occur (i.e., K_s = 1), the difference between the K_c and K_{cb} values on a given day is the magnitude for K_e and, thus, the difference represents the relative proportion of the daily ET_c due to soil evaporation. The soil evaporation for all days in Fig. 2 was small and represented about 3% of the ET_c. However, K_e did increase slightly above basal K_{cb} following both of the irrigations (Fig. 2a, b). During this same three-day interval (DOY 85 to 87), the irrigation applied on DOY 86 exceeded D_r at the end of DOY 86 indicating that some DP occurred. The DP quantified from soil water measurements was 2.2 mm, represented by the downward open triangle on DOY 86 (Fig. 2a).

Paired NDVI observations with derived K_{cb}

Data for the derived K_{cb} and measured NDVI for the first two seasons (1993–1994 and 1995–1996) were used to develop a relationship for describing the wheat K_{cb} values as a function of NDVI. The measured NDVI values were first interpolated linearly, generating separate daily NDVI values for each of the four replicates for both years. The daily NDVI data were then normalized to account for differences in the measured NDVI values at crop emergence that occurred between the two years. The average NDVI value measured at crop emergence for the four replicates in each season was used as the lower limit (minimum NDVI). A maximum NDVI for each season was calculated as the average of the highest three measured NDVI values for each replicate, averaged over the four replicates. Daily NDVI values were normalized as:

$$\mathrm{NDVI}_n = [\mathrm{NDVI} - \mathrm{NDVI}_{\min}]/[\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}] \quad (10)$$

where $\mathrm{NDVI_n}$ is the normalized NDVI, NDVI is the daily value, $\mathrm{NDVI_{min}}$ and $\mathrm{NDVI_{max}}$, are the minimum and maximum NDVI values, respectively. For the 1993–1994 and 1995–1996 seasons, $\mathrm{NDVI_{min}}$ was 0.191 and 0.155, respectively, and $\mathrm{NDVI_{max}}$ was 0.927 and 0.927, respectively.

For each replicate in 1993–1994 and 1995–1996, the average $\mathrm{NDVI_n}$ was determined for each of the 2- to 11-day measurement intervals during the season. The average $\mathrm{NDVI_n}$ values were then paired with the derived K_{cb} values for the corresponding replicate and measurement interval. The time-reference for the paired $\mathrm{NDVI_n} - K_{cb}$ data was taken as the mid-day of the particular measurement interval. Regression procedures were used to model the $\mathrm{NDVI_n} - K_{cb}$ relationship using data for all replicates in 1993–1994 and 1995–1996.

Evaluation data

The $\mathrm{NDVI_n} - K_{cb}$ regression model was tested with data obtained for the 1996–1997 season. As for 1993–1994 and 1995–1996, measured NDVI values for each of the four replicates in 1996–1997 were first interpolated linearly, generating separate daily NDVI values for each of the four replicates. The daily NDVI data for each replicate were then normalized by Eq. 10 using a minimum NDVI value for 1996–1997 (0.185), determined as the average NDVI at emergence for the four replicates. Since the actual maximum wheat NDVI value will not be known until rather late in the wheat season, an assumed $\mathrm{NDVI_{max}}$ value will need to be established ahead of time in order to apply real-time estimation for K_{cb}. Thus, for the purpose of testing the model with the 1996–1997 data, we ignored the fact that we already knew what the actual $\mathrm{NDVI_{max}}$ for 1996–1997 was (0.922) and presupposed that $\mathrm{NDVI_{max}}$ would be 0.927 (i.e., the average $\mathrm{NDVI_{max}}$ as obtained for the 1993–1994 and 1995–1996 seasons). Daily K_{cb} values were calculated with the regression model function for each replicate of the 1996–1997 experiment using daily $\mathrm{NDVI_n}$ values obtained from the normalization of the daily NDVI. Evaluation consisted of comparing the differences between the $\mathrm{ET_c}$ estimated with the FAO-56 dual procedures using the daily K_{cb} values and the measured $\mathrm{ET_c}$ as determined for 27 measurement intervals during the season. Statistical evaluations included the coefficient of determination (r^2), root mean square error (RSME), mean absolute error [MAE] (Legate and McCabe 1999), and the mean absolute percent difference [MAPD] (Kustas et al. 1999).

Results and discussion

Measured evapotranspiration

Measured mean seasonal $\mathrm{ET_c}$ determined from the soil water balance for the C–H plots decreased slightly from the first to the last wheat seasons, as did the calculated seasonal $\mathrm{ET_o}$ (Table 1). For a large majority of the irrigations and for significant rainfall events that were larger than 10 mm during the seasons, deep percolation could not be detected from increased soil water below the estimated root zone following wetting. Thus, for those measurement intervals when DP was not detected, as well as for the intervals when water was not added to plots, potential errors for measured $\mathrm{ET_c}$ due to imprecise DP estimates would be expected to be small, e.g., 5% or less. However, soil water measurements revealed increased moisture below the root zone for several wetting events during each season, which occurred generally towards the latter part of the season when irrigation applications were increased. For these events, the calculated quantities for DP varied from 1 to 22 mm for plot replicates during the three seasons. Thus, for those measurement intervals the uncertainty for DP would generally have a greater impact on the measured $\mathrm{ET_c}$ values. For example, assuming that the largest DP (22 mm) that was determined was accurate to only ±50%, the measured $\mathrm{ET_c}$ for the corresponding interval would be associated with an error on the order of 28%. However, such extreme imprecision for DP was more likely the exception than the rule. When considering all measurement intervals for each season, the mean error for measured $\mathrm{ET_c}$ due to DP uncertainty would be expected to approach the ratio of seasonal DP to the seasonal measured $\mathrm{ET_c}$ for the three seasons (Table 1), or approximately 7–10%. For a majority of intervals, the potential error for $\mathrm{ET_c}$ would be smaller than the mean error, whereas errors larger than the mean could

Table 1 Mean ± standard deviation for measured seasonal irrigation and rainfall, deep percolation, seasonal evapotranspiration ($\mathrm{ET_c}$), estimated basal and soil evaporation quantities of $\mathrm{ET_c}$ from back-calculation procedures, and seasonal reference evapotranspiration ($\mathrm{ET_o}$) for the C–H plot replicates in the 1993–1994, 1995–1996, and 1996–1997 wheat experiments

Wheat season	Irrigation and rain (mm)	Deep percolation (mm)	[a] Seasonal $\mathrm{ET_c}$ (mm)	Basal $\mathrm{ET_c}$ (mm)	Soil evaporation (mm)	Seasonal $\mathrm{ET_o}$ (mm)
1993–1994	710 ± 11	47 ± 13	624 ± 16	581 ± 18	43 ± 2	651
1995–1996	692 ± 5	59 ± 5	599 ± 12	569 ± 14	30 ± 4	639
1996–1997	656 ± 10	42 ± 14	591 ± 25	547 ± 23	44 ± 3	616

[a] Measured $\mathrm{ET_c}$ began with the first soil water measurement after the date of crop emergence in all seasons

be associated with a few intervals during the season when wetting occurred.

Derived K_{cb} estimates

Resulting derivations of K_{cb} values are shown for one of the C–H replicates in the 1993–1994 season in Fig. 3. The measured ET_c values for intervals during the first 37 days past emergence (DPE) and during late season (133–149 DPE) were smaller than the summation of the daily ET_o for those intervals (Fig. 3a). For intervals that occurred from 38 to 132 DPE, measured ET_c was generally greater than the summation for daily ET_o. Back-calculation results indicated that the measured ET_c included considerable soil evaporation following irrigation and rainfall during early season growth prior to 70 DPE when $\asymp$90% canopy cover was attained. The difference between the K_c and K_{cb} value for a given day (Fig. 3b) describes the magnitude for K_e, and thus the magnitude of the contribution of soil evaporation for the measured ET_c. Back-calculations procedures for the C–H replicate resulted in K_{cb} trends consistent with seasonal canopy development patterns, where initially small K_{cb} values increased gradually during early growth to a K_{cb} near 1.0 at 90% cover (70 DPE). The derived K_{cb} values then varied from 1.0 to 1.3 for periods through 132 DPE, and then gradually decreased after 132 DPE during canopy senescence.

As with DP uncertainty for measured ET_c, the accuracy of the various parameter estimates used to describe K_e and K_s in the FAO-56 back-calculations have a degree of uncertainty and, therefore, affect the exactness of the derived K_{cb} values. The seasonal soil evaporation that was estimated (Table 1) represented about 5–7% of the measured seasonal ET_c for the three wheat seasons, which are reasonable values when considering less energy would be available for evaporation for buried emitters as opposed to when water is applied at the soil surface. The values for the derived K_{cb} would be most affected by incorrect K_e estimates during the early season, whereas once full cover is obtained the K_e and K_{cb} values would be suspect only if K_c was greater than K_{cb} by considerably more than 0.05, even following rain events, which was not the case for any of the analyses made. Since the values chosen for the surface soil parameters REW and TEW can influence the estimate of K_e, an analysis was made to examine the effects on the derived K_{cb} values when different values for REW and TEW are assumed instead of those used in the back-calculations, i.e., 10 and 25 mm, respectively. The analysis was performed for the 1993–1994 replicate, whose derived crop coefficients were previously shown in Fig. 3. The FAO-56 tabulated (FAO-56, Table 19) values for the extreme lower and upper limits of the parameters for the soil type were considered, where for the lower limit the REW and TEW were 8 and 22 mm, respectively, and for the upper limit they were 12 and 29 mm, respectively. The results of the analysis indicate that the derived K_{cb} for the replicate would change by about $\pm$5.0% during the first 65 DPE, if either the lower or upper parameter extremes had been used, but there would be little or no difference for derived K_{cb} due to soil parameter values afterwards. However, it was less likely that errors associated with K_s estimation (e.g., an inaccurate rooting depth) had much of an impact on the derived K_{cb}. For all replicates, K_s was calculated to be slightly less than 1.0 for only a few days during each of the three seasons. If for those few instances, the actual

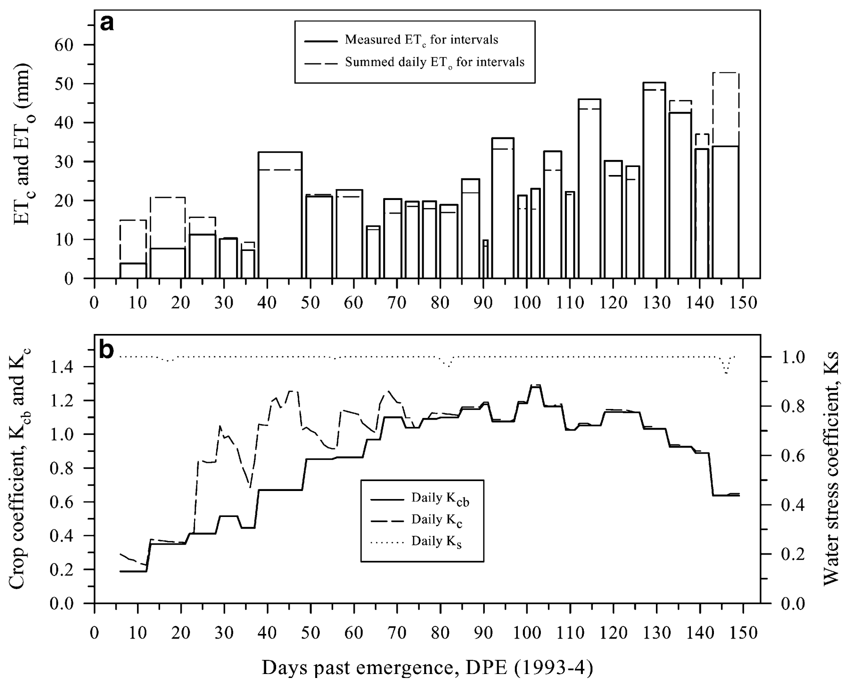

Fig. 3 Seasonal patterns of measured evapotranspiration (ET_c) determined for 27 intervals for a C–H replicate during the1993–1994 wheat season and the summation of daily reference evapotranspiration (ET_o) for each interval (**a**) and the basal crop coefficient (K_{cb}) values derived for each interval, daily estimates of the single crop coefficient (K_c) and water stress coefficient (K_s) as obtained from the ET_c measurements using back-calculations of the FAO-56 dual crop coefficient procedures (**b**)

K_s should have been 1.0 instead of the lower values, the change for the derived K_{cb} during those periods would have been less than 1.0% for all cases. More severe effects of water stress than those calculated were also unlikely due to the frequent sub-surface irrigation schedule used for the C–H replicates for all three wheat seasons.

The derived K_{cb} and $NDVI_n$ values are plotted vs days past emergence for all replicates of the 1993–1994 and 1995–1996 seasons in Fig. 4a, b, respectively. For both years, derived K_{cb} and $NDVI_n$ increased from crop emergence until maximum values for the parameters were attained about 70 DPE. Afterwards, the $NDVI_n$ fluctuated between 0.97 and 1.0 until about 110 DPE for both seasons, and thereafter began to decrease rather sharply through the end of the growing season. The maximum value for K_{cb} was slightly greater than 1.3 during both years. The trends for K_{cb} for both years were similar to those for $NDVI_n$, although the K_{cb} values varied more than for $NDVI_n$ among the four replicates during the seasons. This observation of greater variation for K_{cb} than $NDVI_n$ could imply inexactness for the derived K_{cb} values, as previously discussed. On the other hand, there could have been unobserved plant adaptation effects occurring below ground (e.g., soil or nutrient variability) that may have caused differences in crop water uptake among replicates, and therefore actual differences for K_{cb} that could not be detected from the above-ground reflectance properties of the canopy.

A third-order polynomial regression model was fitted to the combined data from the 1993–1994 and 1995–1996 seasons to describe K_{cb} as a function of $NDVI_n$ (Fig. 5 and Table 2). Although a linear regression of the data in Fig. 5 resulted in an r^2 of 0.85 compared to 0.90 for the third-order polynomial, the third-order model was selected over the linear model because it indicated better overall agreement with the data, particularly for the lowest and highest values obtained for K_{cb} and $NDVI_n$.

Model-estimated versus derived K_{cb} and measured ET_c for 1996–1997

The K_{cb} estimated with the $NDVI_n$ model given in Table 2 for each of the four replicates of 1996–1997 are

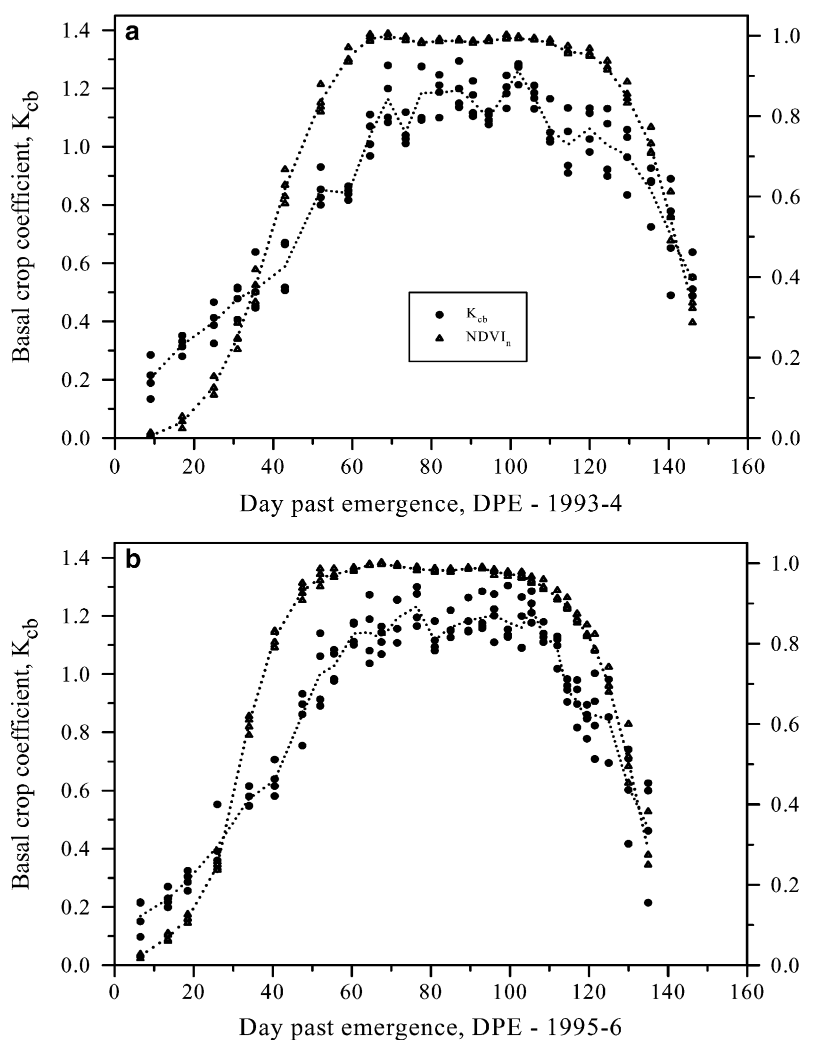

Fig. 4 Derived K_{cb} values and normalized, normalized difference vegetation index ($NDVI_n$) values for all four replicates with days past emergence (DPE) for the measurement intervals of the 1993–1994 (**a**) and the 1995–1996 wheat seasons (**b**)

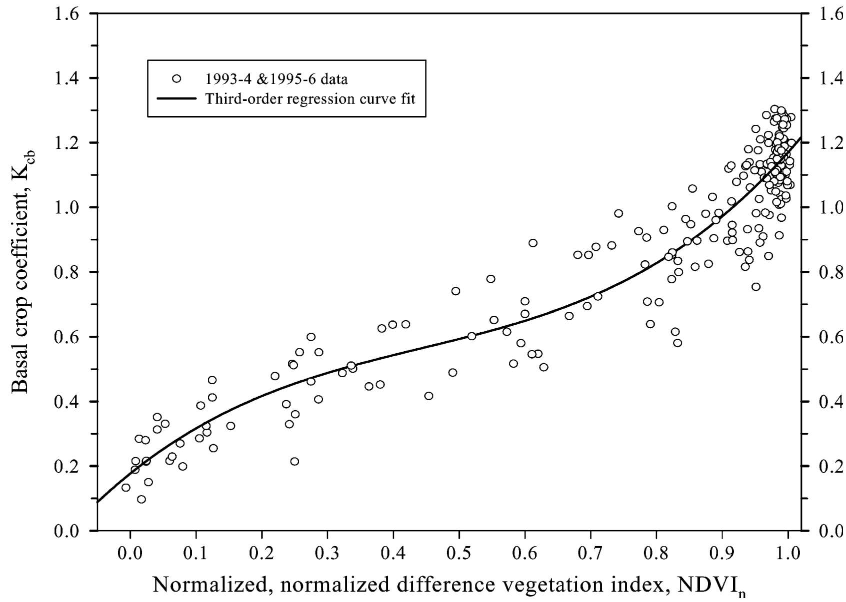

Fig. 5 Derived K_{cb} values shown as a function of the normalized, normalized-difference vegetation index ($NDVI_n$) for combined data of the 1993–1994 and 1995–1996 wheat seasons, and the resultant third order regression model fitted to the data

Table 2 Regression coefficients and statistics for wheat K_{cb} as a function of the normalized, normalized difference vegetation index ($NDVI_n$) for data from the 1993–1994 and 1995–1996 wheat experiments

Regression coefficients[a]				Regression statistics[b]		
a0	a1	a2	a3	r^2	se (K_{cb})	*n*
0.18	1.63	−2.57	1.93	0.90	0.10	232

[a] Regression coefficients are for the third-order polynomial, $K_{cb} = ao + a1X + a2X^2 + a3X^3$, where X is $NDVI_n$.
[b] r^2 is the coefficient of determination, se (K_{cb}) is the standard error of the K_{cb} estimates, and *n* is the number of data points used in the regression

compared to the derived K_{cb} for the 27 soil water measurement intervals made during the season (Fig. 6). For measurement intervals between 10 and 40 days past emergence, the estimated K_{cb} were generally consistent with the derived K_{cb} for all replicates, whereas between 40 and 80 DPE the estimated K_{cb} tended to be somewhat higher than the derived K_{cb}. However, the estimated K_{cb} were consistently lower than the derived K_{cb} for measurement intervals after 80 DPE for all replicates except replicate four, which had estimated K_{cb} values that fluctuated slightly above and below the derived K_{cb} for measurement intervals after 80 DPE (Fig. 6d).

Estimated and measured ET_c are shown as daily averages for each of the 27 measurement intervals in Fig. 7. These ET_c values had trends similar to those between estimated and derived K_{cb} during the season, where ET_c agreement was reasonably good during the first 40 days past emergence, but measured ET_c was generally overestimated for the replicates from 40 to 80 DPE. For replicates one, two, and three, lower than derived K_{cb} estimates after 80 DPE resulted in estimated ET_c that was typically lower than measured ET_c after 80 DPE for those replicates (Fig. 7a–c). Nevertheless, when the measured and estimated ET_c data were applied in linear regression, high r^2 values were obtained for all replicates (Table 3), indicating that the $NDVI_n$-based estimates for ET_c matched the measured ET_c rather well during the season (Fig. 8). Also, the particular trends for the differences noted between estimated and measured ET_c tended to offset when considering the total seasonal ET_c estimates, which were in good agreement with the measured total ET_c (Table 3). The differences between the estimated and measured total seasonal ET_c varied among replicates from −5% (−33 mm) to 3% (18 mm).

Statistics for the estimated and measured ET_c (i.e., the data presented in Fig. 7) calculated separately for each of the four replicates (Table 3) show that the mean and standard deviations (SD) for the estimated ET_c were near those for the measured ET_c for all replicates. The root mean square error varied from 0.42 to 0.71 mm, whereas the mean absolute error varied from 0.31 to 0.49 mm. The mean absolute percent difference was 10% or less among the replicates, which was similar to the 10% variation in K_{cb} that was unexplained by NDVI in the model (Table 2). The statistical evaluations suggest that the remotely-sensed NDVI observations provided reliable K_{cb} estimates for determining the wheat ET_c for all replicates during the 1996–1997 season.

Conclusions

A regression relationship was developed to model wheat K_{cb} values from a normalized NDVI. An initial evaluation of the model suggests that remotely-sensed NDVI observations offer a practical approach for determining real-time K_{cb} and crop evapotranspiration patterns during the wheat season. Because the NDVI-modeled K_{cb} values can be easily incorporated within the FAO-56 dual crop coefficient procedures, as well as other crop

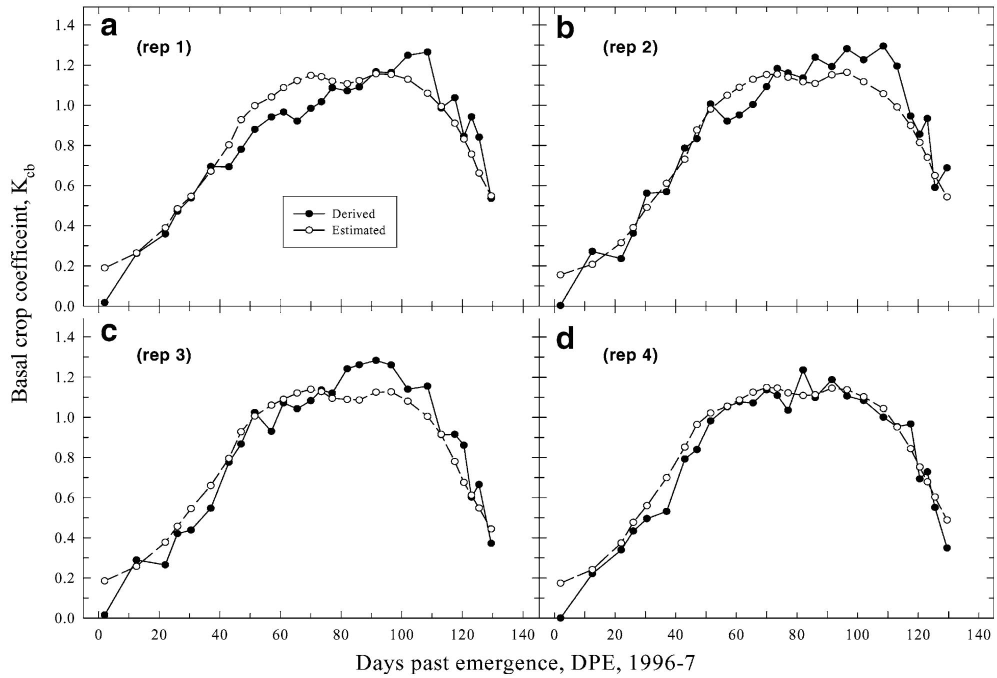

Fig. 6 Derived K_{cb} values obtained for 27 measurement intervals using back-calculations of the FAO-56 dual crop coefficient procedures compared to the estimated K_{cb} for the intervals calculated from normalized, NDVI values using the regression model (Fig. 5 and Table 2) for replicates one (**a**), two (**b**), three (**c**), and four (**d**) of the 1996–1997 wheat season

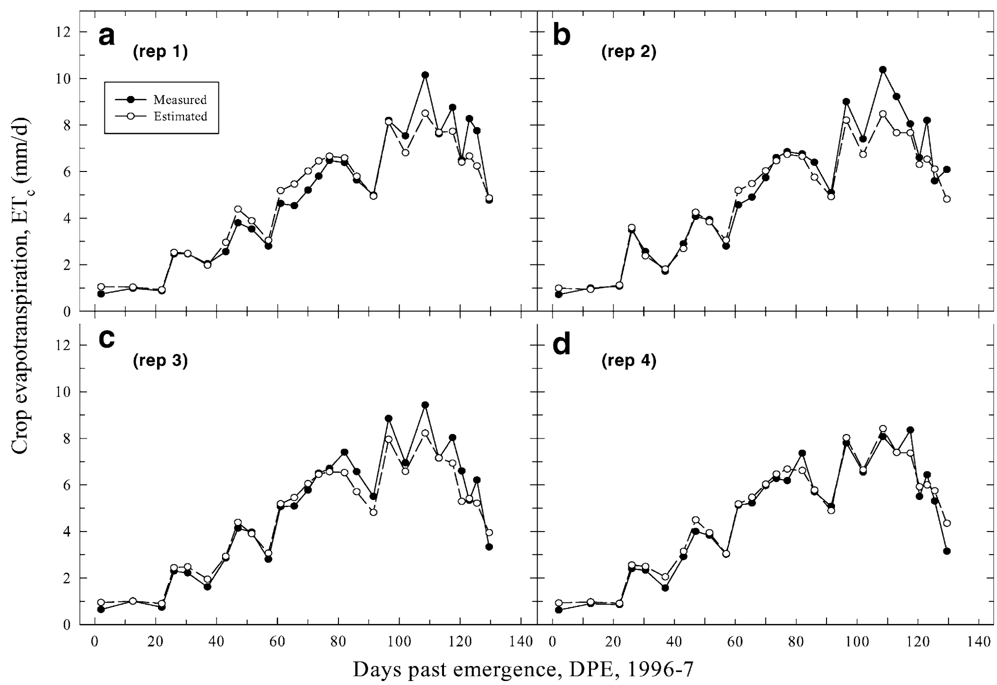

Fig. 7 Measured daily average wheat ET_c obtained for 27 measurement intervals compared to the estimated daily average ET_c for the intervals as determined using the estimated K_{cb} calculated from the regression model within the FAO-56 dual crop coefficient procedures for replicates one (**a**), two (**b**), three (**c**), and four (**d**) of the 1996–1997 wheat season

coefficient algorithms, the NDVI approach could potentially be a significant step towards improving present wheat crop coefficient ET_c estimation. Major advantages for the NDVI-determined K_{cb} compared to conventional time-based K_{cb} curves are that forecasts of the time-scale for crop developmental stages and weather conditions for the cropping season are no longer needed. Another promising aspect for using the NDVI-based wheat K_{cb} is its ability to provide a direct approach for determining actual ET_c conditions when crop growth and water use deviate from optimum conditions. This capability could eliminate the skill, additional field observations, assumptions, and cumbersome procedures required for adjusting generalized K_{cb} curves to reflect sub-optimum conditions. The remote sensing K_{cb} technique may also potentially provide the ability to detect and quantify spatial differences in ET_c within a single field and on a field-by-field basis, information that presently is difficult to obtain without intensive labor. Future work will include testing the wheat K_{cb} model for

Table 3 Measured and estimated total seasonal evapotranspiration (ET_c) and the mean and standard deviation (SD) for the 27 ET_c determinations made for each replicate of the 1996–1997 wheat experiment

Replicate	Measured ET_c			Estimated ET_c						
	Season total mm	Mean mm d^{-1}	SD	Season total mm	Mean mm d^{-1}	SD	RMSE	MAE	MAPD %	r^2
1	594	5.0	2.6	593	5.0	2.3	0.68	0.46	9.6	0.94
2	624	5.2	2.6	591	5.0	2.3	0.71	0.49	9.2	0.95
3	582	4.9	2.5	567	4.7	2.1	0.59	0.44	10.4	0.97
4	564	4.7	2.3	582	4.9	2.2	0.42	0.31	9.1	0.97

Statistics for the estimated mean ET_c are the root means square error (RMSE), mean absolute error (MAE), mean absolute percent difference (MAPD), and the coefficient of determination (r^2)

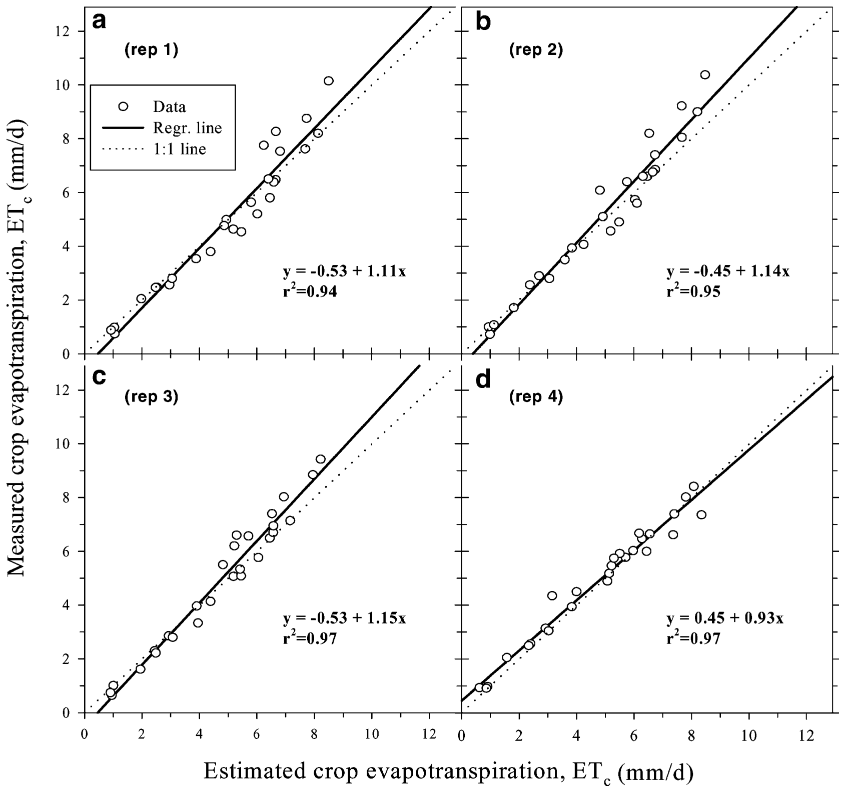

Fig. 8 Measured daily average ET_c vs estimated daily average ET_c and linear regression relationships fitted to the data for replicates one (**a**), two (**b**), three (**c**), and four (**d**) of the 1996–1997 wheat season

estimating ET_c for a wider range of agronomic conditions than those presented in this paper.

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